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Ice Transiting Performance
(Continuous Mode)

Summary Report

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M.V. ARCTIC
ICE TRANSITING PERFORMANCE
CONTINUOUS MODE
SUMMARY REPORT

Prepared for

TRANSPORTATION DEVELOPMENT CENTRE
TRANSPORT CANADA

by

A.C.R. Albery

ALBERY, PULLERITS, DICKSON & ASSOCIATES LTD.

in association with

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17. Abstract

This report presents a summary of the analysis of data relating to the ice transiting performance of the M.V. Arctic, operating in the continuous mode in level ice. The data was acquired over the years 1979-81 during commercial voyages and dedicated trials, by means of manual measurements and a system of instruments recording directly on tapes. From the total data available the useful data was extracted and analyzed to produce an equation representing the performance of the M.V. Arctic in level sheet ice. This equation was tested against the 1974 model tests and correlation was found to be reasonably good. An indication was also obtained of the performance in concentrations of ice floes and broken channels, although the data was inadequate to derive formulae for these conditions.

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17. Resume

Ce rapport présente un sommaire de l'analyse des données relatives à la tenue de l'Arctic se déplacant dans des glaces uniformes, en régime de marche continue. Ces données ont été recueillies entre 1979 et 1981 au cours de voyages commerciaux et d'essais spécialisés. Pour cela, des moyens tant manuels qu'automatiques (enregistrements sur rubans) ont été utilisés. Les données exploitables ont été extraites des données brutes et analysées; il en est ressorti une équation représentant la tenue de l'Arctic dans des glaces uniformes. Cette équation a été confrontée aux résultats des essais sur modèle réduit faits en 1974 et la corrélation obtenue a été jugée relativement bonne. Des valeurs indicatives ont pu également être tirées sur la tenue dans diverses concentrations de floes et dans les chenaux ouverts, l'insuffisance des données empêchant la mise en équation de ces conditions.

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M.V. ARCTIC

ICE TRANSITING PERFORMANCE - CONTINUOUS MODE

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GLOSSARY OF SYMBOLS

The symbols used in this study have been standardized as far as possible to agree with definitions most commonly accepted and are not necessarily those of the original authors of the various equations to which reference is made. Special symbols not included in the glossary or special meanings given to symbols are defined where they occur.

Roman Symbols	Definition	Dimensions
B	Beam of Ship	L
C_b	Coefficient of resistance due to breaking ice	-
C_s	Coefficient of resistance due to submerging ice	-
C_v	Coefficient of resistance due to velocity	-
E	Elastic or total strain modulus	$L^{-1}MT^{-2}$
H	Draft of ship	L
L_w	Cube root of Volumetric Displacement	L
R_t	Total resistance due to ice and water	LMT^{-2}
R_i	Resistance due to ice	LMT^{-2}
R_b	Resistance due to breaking ice	LMT^{-2}
R_s	Resistance due to submerging ice	LMT^{-2}
R_v	Resistance due to velocity	LMT^{-2}
R_{ow}	Resistance in open water	LMT^{-2}
V	Speed of ship	LT^{-1}
f_d	Coefficient of dynamic friction	-
g	Acceleration due to gravity	LT^{-2}
h	Ice thickness	L
h_s	Snow depth over ice	L

Greek Symbols	Definition	Dimensions
γ_i	Weight density of ice	$ML^{-2}T^{-2}$
γ_Δ	Weight density of water less ice	$ML^{-2}T^{-2}$
η	Friction form coefficient, as defined in text	-
η^2	Shimansky bow form coefficient (ice cutting)	-
μ	Friction form coefficient, as defined in text	-
μ_o	Shimansky bow form coefficient (ice breaking)	-
ρ	Mass density, as defined in text	ML^{-3}
σ	Strength of ice, flexural where not defined	$L^{-1}MT^{-2}$
σ_f	Flexural strength of ice	$L^{-1}MT^{-2}$

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1. INTRODUCTION

The M.V. Arctic is an Arctic Class II bulk carrier which has characteristics as shown in Table 1.1. It was designed for possible service in the Great Lakes, the St. Lawrence River and the eastern Arctic Islands within the navigation limits prescribed by the Canadian Arctic Shipping Pollution Prevention Regulations. Whilst designed essentially for commercial operation, advantage was taken to install a comprehensive system of instruments for monitoring and recording on tape the performance of the ship in ice. Data have been acquired over the three operational seasons 1979-81 both during commercial voyages and certain dedicated trials off Baffin Island, in the Saguenay River and in Lake Melville.

Although structural, propulsive manoeuvring and ice ramming performance was also tested and monitored, this summary report deals only with performance in the continuous mode when transiting level sheet ice, broken channels and ice floes in various concentrations.

The full details of the Study are contained in the Main Report, TP-5170E entitled "M.V. Arctic - Ice Transiting Performance - Continuous Mode" submitted to the Transportation Development Centre, Transport Canada, in May 1984.

TABLE 1.1

M.V. ARCTIC - SHIP CHARACTERISTICS

Length Overall	209.55 m
Length Between Perpendiculars	196.60 m
Moulded Breadth (Beam)	22.86 m
Moulded Depth	15.24 m
Moulded Draught	10.97 m
Summer Draught	10.82 m
Block Coefficient	0.753
Prismatic Coefficient	0.761
Light Ship	9,276.1 t
Displacement at 10.81 m draught	37,724.1 t
Dead Weight at 10.81 m draught	28,448.0 t
Cargo Capacity	34,448.0 cubic metres
Propulsion Machinery - MAN Diesel	11,014 kilowatts
Generators	900 kW x 3
Complement	40
Speed on Trials	15.5 knots
Cruising Range	14,000 nautical miles

2. EXISTING RESEARCH

As a background to the analysis of the performance of the M.V. Arctic in various types of level ice, a review was made of existing knowledge and previous attempts to formulate equations for predicting the resistance of ice to the motion of a ship. This review is given in Appendix A of the main report, Ref: TP-5170E and may be summarized as follows:-

Level ice conditions may be divided into three main classifications:-

(a) continuous level sheet ice.

(b) pack ice or concentrations of ice floes.

(c) channels previously broken in sheet ice.

Historically, most research has been carried out on the resistance of continuous sheet ice, probably because it is more amenable to rigorous treatment and also because this is the predominating form of ice in the Baltic Sea where most early full-scale tests were undertaken by Russia and Finland.

Although equations for the resistance of sheet ice have been presented by researchers since the end of the nineteenth century, it was Kashtelyan[1] who presented in 1968 the first generally accepted analytical approach to the problem. As a result of the work of Kashtelyan there has, until recently, been general acceptance of the thesis that the resistance of ice to the motion of a ship is made up of three main components.

R_b, the resistance due to breaking the ice which is independent of velocity.

R_s, the resistance due to submerging the broken ice which is independent of velocity.

R_v, velocity dependent resistance.

Kashtelyan's general equation in its final simplified form is

$$R_t = 0.004B\sigma_f h\mu_o + 3.6\gamma_i Bh^2\mu_o + 0.25\, B^{1.65}.\frac{hV}{\eta_2} + R_{ow} \quad \ldots\ldots\ldots (1)$$

where μ_o and η_2 are coefficients depending on the shape of the bow of the ship and R_t is in tonnes force.

Kashtelyan's numerical coefficients were derived mainly from model and full-scale tests on the Russian ice-breaker Ermak. The coefficients for the first two terms are dimensionless and applicable to any consistent set of units. However, the third term is not dimensionally correct so that the value of 0.25 applies only to metric units.

The general view of most subsequent researchers has been that all terms should be dimensionally correct for proper comparison of model and full-scale results and for confidence in extrapolition to larger ships. The most widely accepted form of equation for ice resistance only was

$$R_i = C_b\sigma_f Bh + C_s\rho gBh^2 + C_v\rho gBh^2\left(\frac{V}{\sqrt{gh}}\right)^n \quad \ldots\ldots\ldots (2)$$

or in a dimensionless form:-

$$\frac{R_i}{\rho gBh^2} = C_b\,\frac{\sigma_f}{\rho gh} + C_s + C_v\left(\frac{V}{\sqrt{gh}}\right)^n \quad \ldots\ldots\ldots (3)$$

where C_b, C_s and C_v are coefficients dependent on bow shape and friction and ρ is variously the density of water, ice or the difference between the two, according to the perception of the researcher.

The actual selection of parameters forming each dimensionless term is still very much a matter of judgement. For instance there is some evidence that both the waterline length, L, and the draft of the ship, H, affect the resistance and should be included in the equation. There is also a recent realization that the breaking component of resistance is much greater than previously supposed and a growing opinion that R_b varies with h^2 and R_s with h, rather than R_b with h and R_s with h^2.

Another assumption implicitly made in nearly all resistance equations

is that ice is always broken in bending and that only flexural strength is important. This may be so if the bow is designed to ensure breaking in bending only, but, in the case of the typical ice-breaker bow, there is usually some crushing at the shoulders and often the need for some of the ice to break in shear or buckling. Allied to the mechanism of breaking is the importance of E, which, in the case of ice is not a pure elastic modulus but, rather, the total strain modulus including plastic deformation. Since the process of ice-breaking is the intermittent one of breaking off multiple pieces of ice, there is no continuous steady force and it is generally argued that the effective resistance is the time integral of the energy expended in breaking divided by the distance travelled. Since the energy expended depends on the deflection of the ice as well as its resistance to bending or other failure, the value of E would seem to be important. However, most equations based on static analysis do not include E as a variable parameter.

Recent research has not only shown that the breaking component of resistance is much greater than previously supposed, but also that hull/ice friction plays a very important part. The magnitude of the frictional effect is closely related to the shape of the bow, particularly the vertical flare angle at the shoulders where the vessel approaches its maximum beam. If the flare angle has a tangent less than the coefficient of friction, the ice will have difficulty in sliding down the hull to break in bending, thus causing jamming at the shoulders and crushing of the ice until it breaks in shear or buckling. The extra force thus imposed on the sides of the vessel will then cause greatly increased longitudinal friction opposing motion of the ship. The importance of shoulder resistance has led to the spoon-shaped ice-breaking bows of the Dome Petroleum icebreakers Kigoriak and Robert Lemieux.

One of the most important questions posed by ice-breaking research is the validity and reliability of model testing in artifical saline ice. It is virtually impossible with ordinary saline ice to satisfy simultaneously the laws of similarity for both the bending strength of the ice, σ_f, and its strain modulus, E. In order, therefore, to maintain a σ_f/E ratio close to real sea ice, the strength of the model ice is usually made greater than required by dimensional similarity and compensated for by subsequent

adjustment. However, the methods used for adjustment have been questioned by some experts and there remains some doubt regarding their validity. The recent introduction of carbamide ice, which is claimed to satisfy more nearly the similarity laws for ice modelling, may solve some of the earlier problems, but experienced analytical judgement will still be needed to correctly interpret the model test results.

In conclusion, it may be said that the science of predicting the resistance of ice to the motion of a ship is still far from perfected. Equations can be produced from model or full-scale test to predict the performance of a particular ship but the equations will usually only be valid for that ship and within the range of the test data. An acceptable general equation for predicting the performance in ice of ships of various shapes and sizes in a wide range of ice conditions has yet to be developed.

3. THE SCANNING AND EXTRACTION OF DATA FROM THE M.V. ARCTIC DATA BANK

The data relating to the performance of the M.V. Arctic during the three operating seasons 1979-81 were collected on 163 tapes. The contents of each of the tapes were summarized in the Master Data Package which showed that information was recorded from 212 sensors, of which 39 sensed parameters relevant to the ship's performance in ice. Unfortunately many of the performance parameters were frequently not recorded due to sensor difficulties. In 1979 the most critical parameters of thrust, torque, shaft speed and ship speed were absent from most tapes and in 1980 shaft speed and ship speed were still not available. Only in 1981 were these items properly recorded. It was, therefore, decided to spend most effort on the 1981 data tapes.

The system used to read and analyze the data tapes included a DEC PDP-11 mini-computer with a tape drive, hard disc drive, video graphics terminal and matrix printer. An available software program, originally designed for reading tapes with foreign formats was modified to suit. This program already incorporated the code required to control the tape drive and transfer data in block form from tape to computer memory. The code required to interpret the data blocks, convert the measured parameters into engineering units and present data in an easy to use form had to be added. In order to determine the accuracy, noise levels and general characteristics of the recorded signals, a second program was written to display any chosen parameter graphically on the video terminal. This visual technique proved to be a very effective way of examining the various data signals and selecting steady state data points.

The data of interest covering thrust, torque, ship speed, shaft RPM, wind speed, wind direction and propeller pitch were stored on disk. Time-history plots of the seven parameters were then produced resulting in 3000 plots covering about 100 hours of data.

4. REDUCTION AND SUMMARY OF DATA

Because insufficient data on ice conditions were recorded during the commercial voyages, emphasis had to be placed on the data from the following dedicated trials:

- Saguenay River, 1979/80.
- Baffin Island, 1980.
- Lake Melville, 1981.

In the Saguenay River trials ship speed was measured only by Doppler instruments and recorded on tape. In the Baffin Island and Lake Melville trials ship speed was also measured manually by stop-watch timing between markers on the ice. The manually measured speed showed that the Doppler speeds were often inaccurate and the latter therefore were corrected by calibration with the manual measurements.

In addition to speed, the data tapes were used to produce time based plots of propeller RPM, propeller pitch, propeller thrust, shaft power, wind speed and wind direction. Propeller pitch and thrust and shaft power were correlated with the self-propelled model tests in clear water (N.R.C. Report LTR-SH-349) and small adjustments made. To derive total thrust the duct thrust was added and, to determine the thrust required to overcome ice resistance, the thrust deduction and open water resistance was deducted. The resulting data are tabulated in Section 4 of the main report, Ref: TP-5170E.

The properties of the ice encountered during the trials were approximately as given in Table 4.1.

As previously mentioned, the completeness and quality of data available from the voyages is generally poor. A preliminary assessment of the availability of useful data was made by review of the master data package and selected video tapes. From this review and trials reports, voyage segments which appeared potentially useable for analysis of performance in pack ice or broken channels were identified. From these voyage segments data were selected and tabulated.

TABLE 4.1

ICE PROPERTIES DURING TRIALS

Test Site	Thickness, m	Strength, kPa	Strain Modulus
Saguenay River*	0.37 - 0.50	425	1875
Baffin Island, 2**	0.185	235 ± 25	400 ± 35
" " 2***	0.185	350 ± 80	525 ± 75
" " 3	0.315	340 ± 85	1090 ± 390
" " 4	0.39	330 ± 115	1320
" " 5	0.32	410 ± 70	1400 ± 250
Lake Melville	0.58 - 1.07	267	2320

* Derived not measured

** Beam length parallel to C-axis

*** Beam length perpendicular to C-axis

5. DEVELOPMENT OF PERFORMANCE FORMULAE

It had been the intention at the start of the study to develop formulae representing the performance of the M.V. Arctic in all three types of level ice conditions -

(a) continuous sheet ice
(b) pack ice
(c) broken channels

However, the data were inadequate to produce meaningful formulae for performance in pack ice and broken channels because the size and thickness of ice floes were not measured or recorded. As a result the development of a formula or equation to represent the performance of the M.V. Arctic has been limited mainly to its performance in continuous sheet ice.

5.1 Performance in Continuous Sheet Ice

As demonstrated in Section 2 of this Report, the development of general equations to predict the performance of ships in continuous sheet ice is still an inexact science. The main advance in recent years is the realization that the ice-breaking component of total resistance is much greater than previously thought and that friction plays an important part in relation to the shape of the bow.

As a result of the model tests on the M.V. Arctic in 1974, the Baffin Island trials in 1980 and the Lake Melville trials in 1981, three equations were produced by others to represent the ship's performance in continuous ice. All these were based on equations of the Kashtelyan type with one or more numerical coefficients or indices modified by regression analysis to fit the test data. Whilst this procedure can give good results within the limits of the test data, the resulting equation cannot be used with confidence for predicting performance outside the range of the data. It was therefore decided to attempt to develop an equation from more fundamental considerations based on an existing equation with a good analytical basis.

A total of some forty formulations by various authorities were examined and the following four were selected as suitable with some modifications for application to the M.V. Arctic data.

References

Kashtelyan	(1)
Enkvist	(3)
Poznyak & Ionov	(4)
Carter	(5)

These formulations fall into two types as follows:

A. The equations of Kashtelyan, Enkvist and Poznyak and Ionov which are based on the principle that ice resistance consists of three components so that:-

$$R_i = R_b + R_s + R_v$$

B. The equation of Carter who recently developed a different approach, based on quasi-static analysis which is then modified by dynamic considerations.

Table 5.1 shows various equations of Type A, of which those numbered 2, 3 and 7 in the Table were selected for testing against the trials data. The testing process revealed the following resistance relationships for the M.V. Arctic.

(1) Ice Resistance varies approximately linearly with velocity.

(2) The non-velocity dependent resistance ($R_b + R_s$) varies approximately with h to the power of 1.8.

(3) Based on very limited data, the velocity dependent resistance appears to vary approximately with $h^{1.5}$.

TABLE 5.1

Selected Ice Resistance Predictor Equation Forms

Author	Breaking R_b		Submerging R_s		Velocity R_v
1. Kashtelyan	$C_b\sigma_f Bh$	+	$C_s\rho_i gBh^2$	+	$C_v B^{1.65} hV$
2. Kashtelyan (Mod.)	$C_b\sigma_f Bh$	+	$C_s\rho_i gBh^2$	+	$C_v^1\rho_i gBH^{0.5}h^{1.5}\frac{V}{\sqrt{gh}}$
3. Enkvist[1]	$C_b\frac{\sigma_f^2}{E}Bh$	+	$C_s\rho_\Delta gBhH + C_s^1\rho_w gBh^2$	+	$C_v\rho_i gBh^2V^2/gh$
4. Poznyak et. al.[2]	$C_b\sigma_f h^2(C_1B + C_2L)$	+	$C_s\rho_\Delta gBhL$	+	$C_v\rho_i gB^2h\frac{V}{\sqrt{gL}}$
5. Poznyak (Mod. Eqn.)	$C_b\sigma_f h^2(C_1B + C_2L)$	+	$C_s\rho_\Delta gBhL$	+	$C_v\rho_i gBL^{0.5}H^{0.5}h\frac{V}{\sqrt{gL}}$
6. (Alternative form)	$C_b\sigma_f h^2(C_1B + C_2L)$	+	$C_s\rho_\Delta gBhL$	+	$C_v\rho_i gBH^{0.5}h^{1.5}\frac{V}{\sqrt{gh}}$
7. Poznyak (Mod. Eqn.)	$C_b\sigma_f h^2(C_1B + C_2L)$	+	$C_s\rho_\Delta gBhL$	+	$C_v\rho_i gB\left[\frac{H}{L_w}\right]^{0.5}h^2\cdot\frac{V}{\sqrt{gh}}$

NOTE: (1) The third term, $C_s^1\rho_w gBh^2$, is part of an expression derived by Enkvist for R_v which is not actually dependent on velocity.

(2) The first term is not dimensionally correct and, for comparison of full-scale with model tests should be replaced by a dimensionless coefficient such as $\frac{C_1B + C_2L}{L_w}$ where L_w is the cube root of the volumetric displacement.

Following extensive testing of the three Type A equations against the M.V. Arctic data, it was concluded that resistance was best expressed by the following modified form of the Poznyak and Ionov equation.

$$R_t = 0.035\sigma_f h^2\{\mu_1\} + 0.029\gamma_\Delta hBL\{\mu_2\} + 7.4\gamma_i B\left(\frac{H}{L_w}\right)^{\frac{1}{2}} h^2 \cdot \frac{V}{gh}\{\mu_3\} + R_{ow} \quad \ldots (4)$$

The above is the generalised equation where μ_1, μ_2 & μ_3 represent the form-friction coefficients for the particular ship. The equation of total resistance (ice and water) reduces to the following when the values of hull dimensions and bow geometry are inserted for the M.V. Arctic and assuming a dynamic coefficient of friction of 0.03 for Inerta 160 hull coating.

$$R_t = 3.33\ \sigma_f\ h^2 + 169\ h + 241\ Vh^{3/2} + R_{ow} \text{ (kilo Newtons)} \quad \ldots\ldots\ (5)$$

where σ_f = ice flexural strength (kilo Pascals)
h = ice thickness (metres)
V = ship speed (metres per second)

The derivation and resulting form of the Type B equation of Carter is attractive but, before it can be accepted, an explanation is required of the reason why it gives values of resistance which are too low for the Lake Melville trials with the assumed friction coefficient of 0.03.

In addition to the four Type A and B equations selected for testing against the trials data, S.T. Mathews derived an entirely new form of equation based on dynamic consideration alone, which is described in an Appendix to the Main Report. Mathews derived friction coefficients to suit the respective trials data and, using these coefficients, his equation fits well over the limited range of the trials data. The equation will, however, need to be tested over a greater range of data and for other ships of different shapes and sizes.

The final evaluation led to the selection of a Type A equation, specifically that based on Poznyak and Ionov cited above.

5.2 Performance in Broken Channels and Pack Ice

In the absence of any measurements of floe sizes and thicknesses an assessment of typical ice condition was made for the location and time of year of the relevant recorded voyage data. Based on this, it was determined that performance in concentrations of pack ice was realistically given by the simple relationship given by Kashtelyan[1].

$$R = (C_k + 9V^{1.3})h^{1.2}$$

where h = ice thickness (0.8 to 2 m)

V = average transit speed (0.5 to 13 knots)

C_k = empirical coefficient based on floe size (20 m to 1.5 m)

This prediction presents a time averaged resistance which must become increasingly coarse as floe size increases and concentration decreases (short bursts of continuous icebreaking interspersed with open water).

The above formulation has been used to prepare Figures 5.1 and 5.2 which show the variation in the M.V. Arctic predicted broken ice resistance with ice thickness and floe size.

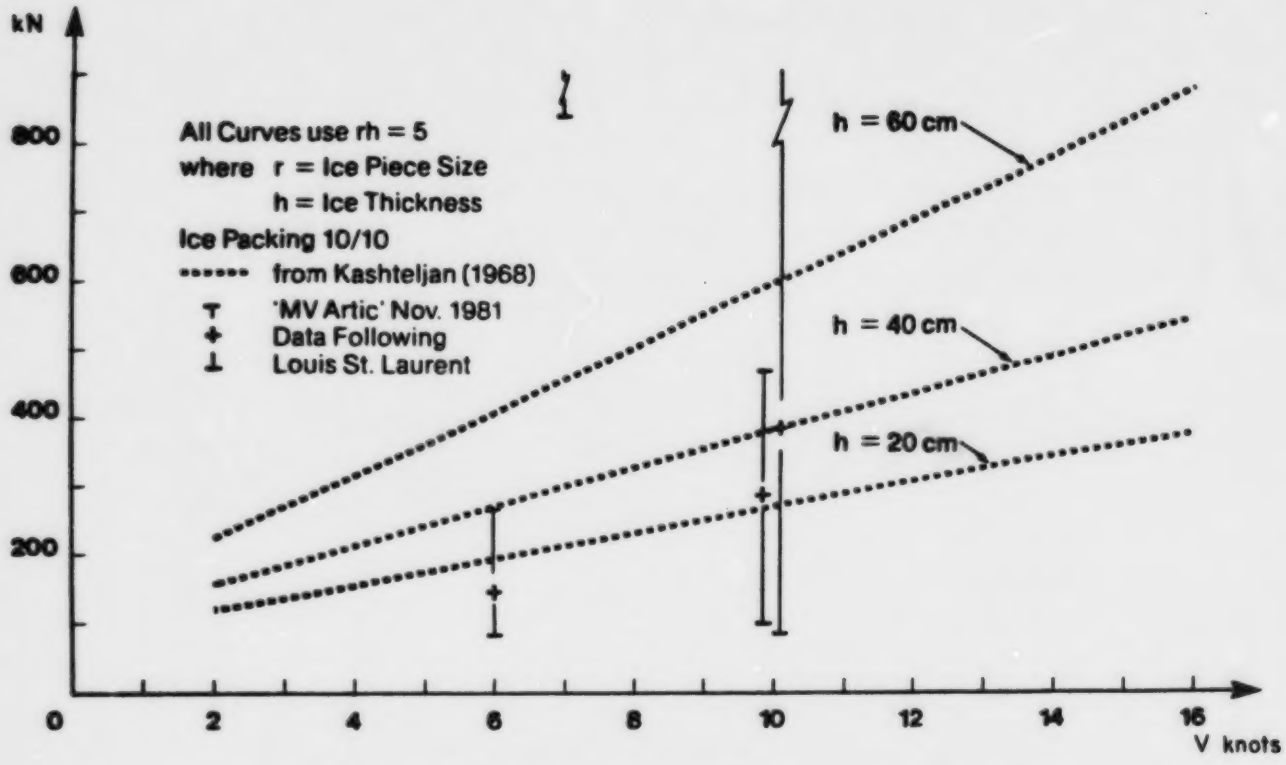

Figure 5.1 Variation in Predicted 'MV Arctic' Broken Ice Resistance with Ice Thickness

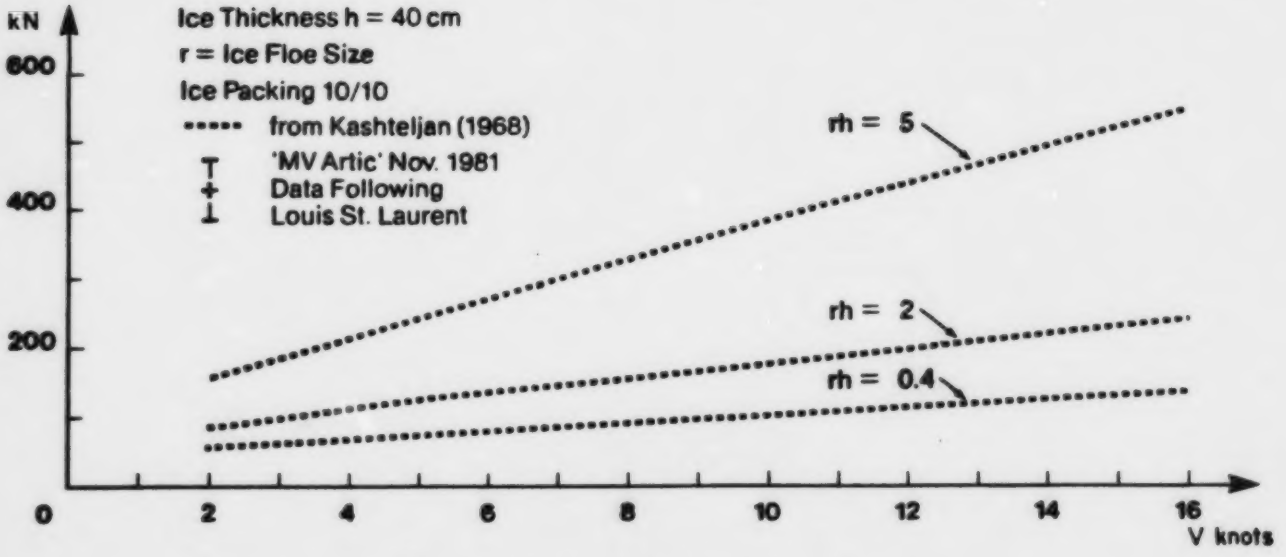

Figure 5.2 Variation in Predicted 'MV Arctic' Broken Ice Resistance with Ice Floe Size

6. GRAPHICAL PRESENTATION OF PERFORMANCE

As demonstrated in Section 5, the modified Poznyak and Ionov equation (Eqn. 4) can be accepted as being a reasonable formulation of the performance of the M.V. Arctic in continuous level sheet ice during the various trials carried out in 1979-81. The equation can be used for predicting the performance of the M.V. Arctic with its present bow shape provided the strength of the ice to be traversed and the hull/ice dynamic friction coefficient can be assessed with reasonable accuracy.

Since Equation 4 in its full form takes the bow angles into account, it should also be applicable to changes in bow shape unless such changes are of a radical unconventional form. The equation should, however, be tested against the model test results for an altered bow shape.

The performance of the M.V. Arctic as given by Equation 4 is shown in Figure 6.1 in the form of the relationship between total resistance, speed, power and ice thickness for a flexural ice strength of 350 kPa and a coefficient of friction between hull and ice of 0.03.

A dynamic friction coefficient of 0.03 fits well with the dedicated trials data and is a reasonable value for a hull coated with Inerta 160 or equivalent and for ice with negligible snow cover. At a reasonable speed of 2 m/s (3.9 knots) for continuous progress through ice, Figure 6.1 indicates the following relationship between ice thickness and required power for a vessel of the size and shape of the M.V. Arctic.

Ice thickness	0.61 m	required power	5,600 kW
Ice thickness	0.85 m	required power	11,000 kW
Ice thickness	1.00 m	required power	16,500 kW

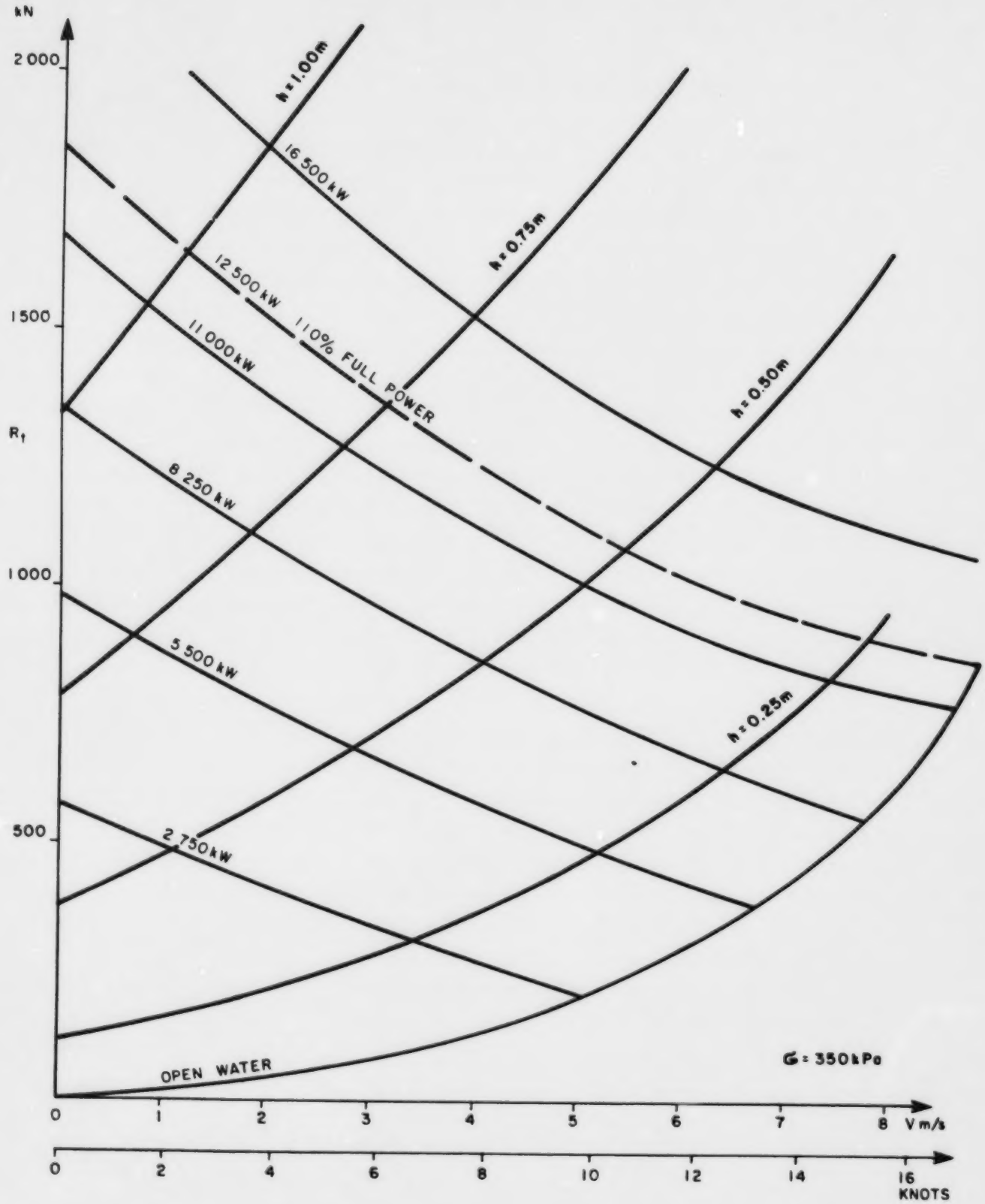

FIGURE 6.1 M.V. ARCTIC SHEET ICE PERFORMANCE DIAGRAM FOR f_d = 0.03

7. POWER PROVISIONS OF CASPPR[6]

The M.V. Arctic is an Arctic Class 2 vessel. The installed power of 11014 kW is 17% more than that required as a minimum for a Class 3 ship according to Schedule G of the Regulations and 2.6 times that required as a minimum for a Class 2 ship. The astern power level requirement is 70% of that ahead and this requirement is met with similar factors to those ahead.

The actual full-power ice performance as given by Figure 6.1 for a reasonable continuous speed of 2 m/s is 0.85 m ice thickness.

In addition to the power requirements for continuous motion in level sheet ice, it is relevant to consider the definition of Arctic Classes according to the limiting seasons for operating into permitted zones.

The M.V. Arctic's limiting operation as a Class 2 ship is into Zone 13, entering no earlier than June 25 and leaving no later than November 15 in each year. If she were classified as an Arctic Class 3 ship, the earliest entry into and departure from Zone 13 would be June 10 and December 31, respectively.

In Voyage 5 propeller thrusts often exceeded 800 KN corresponding to shaft powers exceeding 9500 kW. These thrust levels were associated with as many as 20 thrust level changes in 15 minutes associated with the necessity for backing and ramming and this following the CCGS Louis St. Laurent.

For this Class 2 operation it is clear that the CASPPR minimum requirement of 4174 kW of installed power is inadequate.

It is also clear that a Class 3 operation with extended dates earlier than Voyage 1 and later than Voyage 5 with a CASPPR power of 9390 kW could not have been carried out unassisted.

It is evident, therefore, that the minimum CASPPR power requirements for Classes 2 and 3 are too low by a large factor for a cargo vessel of the shape of the M.V. Arctic operating within the seasons now permitted for Zone 13.

8. MODEL VERSUS FULL SCALE DATA

In addition to open water model tests by NRC, ice resistance model tests were carried out by Arctec in 1974[7]. These included runs with hulls of different roughness but the tests carried out to determine the actual hull/ice coefficient of friction are open to a different interpretation from that reported. Since friction is an important component of ice resistance there must be some doubt regarding the interpretation of the model tests as a whole.

With a reasonable assumption regarding the coefficient of friction of the model hull, the modified Poznyak and Ionov equation agrees well with general trend of the model test data points when plotted on a non-dimensional basis. There is, however, much scatter of the model data points and, when a direct comparison of the model test resistance is made with that given by the Modified Poznyak and Ionov equation (Eqn. 4), there is a wide divergence of results, as shown in Table 8.1. This is particularly so in tests 4.1 to 4.4 where the model ice had a very high equivalent strength of 1503 kPa and an above average thickness of from 1.32 to 1.47 metres. Without further research it is not possible to tell whether the model seriously under-estimated the resistance in thick high- strength ice or whether Equation 4 over-estimates the resistance. The question is, however, an important one and should be investigated.

TABLE 8.1

MODEL TEST RESISTANCE VALUES COMPARED WITH EQN. 4

Sheet Tests	Value of R_t in kN	
	Model Tests by Arctec	Calculations from Eqn. 4
2-1	5,740	4,143
3-1	2,133	1,589
3-2	1,373	905
4-1	11,026	21,700
4-2	11,387	22,595
4-3	10,747	22,453
4-4	9,470	18,053
5-1	2,403	2,799
6-1	2,627	2,622
6-2	1,675	2,102
7-1	2,119	1,872
7-2	1,158	1,033
8-1	1,282	1,994
8-2	677	1,661
8-3	398	--

9. HULL GEOMETRY

During the past several years, there has been a growing recognition of the importance of hull geometry and friction in relation to the ice-breaking process. Concurrently, it has become apparent from model and full-scale tests and new analytical approaches that the breaking component of total resistance is much greater than originally supposed by researchers such as Kashtelyan and Enkvist.

Until recently most emphasis was placed on the shape and angle of the ice-cutting stem. However, in the case of a large vessel, the ice-cutting stem does not usually break the ice over the whole width of the bow and the sides of the bow have to widen the channel by breaking off cusps of ice as the vessel proceeds.

It can in fact be shown that the shoulder resistance to breaking may be considerable and only limited by shear or buckling strength of the ice if the friction is too great in relation to the vertical angle of the shoulders.

The fundamental requirement for any low resistance ice-breaking bow is to break as much of the ice as possible in pure bending to the full width of the vessel and, in this regard, the minimum flare angle is critical for a conventional type of ice-breaking bow. Improvements to the bow of the M.V. Arctic may, however, be constrained by its function as an ocean-going bulk carrier and by its need to pass through the locks of the St. Lawrence Seaway.

The shape of the hull astern of its section of maximum water-line beam is relatively unimportant as far as ice transiting under normal conditions is concerned. However, the long length of the M.V. Arctic may result in greatly increased resistance under wind or current conditions that produce internal pressures in the ice field. Such conditions appear likely to have been present during tests on November 26, 1980 in thin ice in Navy Board Inlet.

There is evidence that the draft of the vessel has some effect on the velocity dependent resistance and this is taken into account in Equation 4.

10. EFFECT OF BUBBLER SYSTEM

The dedicated trials in Lake Melville indicate that the use of the bubbler system did not provide any reduction of resistance under the conditions tested and, in fact, increased resistance in ice with a thickness of about 0.64 m. The Baffin Island trials data also indicate that the bubbler system on the M.V. Arctic is relatively ineffective. The Saguenay River trials data appear to show an increase in resistance with bubbler on but this may be misleading in view of the slightly greater ice thickness. The reasons for the ineffectiveness of the bubbler system require detailed analysis but the following possible explanation is offered for further consideration.

In the first place, the essential purpose of a bubbler system is to reduce friction and will obviously be more effective in conditions where hull/ice friction is high. With its Inerta 160 coating, the M.V. Arctic has a naturally low surface friction and the scope for improvement with bubblers is small. Also, nearly all the dedicated trials were carried out in conditions of negligible or small snow cover which again would reduce the potential benefit of bubblers.

Another factor contributing to the ineffectiveness of the bubblers may be the vertical sides of the vessel astern of the shoulders. If the vessel has a flare angle, the air bubbles and induced water movement will cling to the surface of the vessel and ensure an effective lubricating film. On the other hand, with a vertical surface the bubbles may dissipate laterally, thus reducing the movement of water over the surface of the hull in the region of the hull/ice contact.

11. EVALUATION OF RIGID BODY MOTIONS

The evaluation of rigid body motions was a desired output from the study. However, at an early stage of attempts to do this evaluation, it was found that no useful information could be obtained from the tapes of the six accelerometers and two gyros with which the M.V. Arctic was equipped. The main reasons for this were:-

- Most of the accelerations experienced by the ship were smaller than the resolution limit of the data collection system.
- This was found to be true even in the ramming mode, which one would expect to be more severe than the continuous mode.
- The data recording was incomplete since many channels were frequently absent or inactive.
- Although some channels looked reasonable at times, their accuracy could not be verified.
- Attempts to verify certain channels by computing velocities indicated that the data was most likely false.

Based on the above findings the conclusion was drawn that any observations, with respect to the motions of the ship during the continuous ice-breaking mode, could not be made with any confidence. There is a remote possibility that if the investigation was pursued, more positive results could be obtained; however it was felt that any further effort would not be worthwhile.

12. COMMENTARY ON INSTRUMENTATION SYSTEMS

Since this project is restricted to the analysis of the M.V. Arctic's ice transiting performance in the continuous operating mode, the comments on the instrumentation system are restricted to data relevant to analysis.

The original design of the data system appeared to be thoroughly complete, in that all the parameters one might require for a performance analysis had been included. The execution of the system was less satisfactory, however. From the very beginning of operation and for a full two years thereafter, some of the most fundamentally important sensors were operating poorly or not at all. One of the most glaring examples of this is the sensors for measuring the engine and shaft RPM - a measurement which is generally considered to be one of the easiest to obtain with accuracy and reliability.

The data that was collected would be more useful and complete if more detailed logs of events, ice conditions and backup readings were kept. More frequent and better documented calibration checks of the data systems would also have been invaluable. In general, far more useful information would have been obtained if more short, controlled and well documented test runs were recorded rather than lengthy tapes of undocumented voyage data.

To prevent many of the aforementioned difficulties in future projects, extensive development of the data acquisition software will have to be undertaken to improve upon its utility features and error checking capabilities. Some of the features that should seriously be considered are given in the Main Report.

13. SUMMARY OF CONCLUSIONS

13.1 The review of existing ice resistance research shows that the science of predicting the resistance of ice to the motion of a ship is still very much in its infancy. Although a great deal of data has been obtained in recent years from full-scale and model tests there is still no generally accepted equation for predicting the performance of ships of various shapes and sizes in level ice of various thicknesses and physical properties.

13.2 The data acquired over the three years 1979-81 by the instrumentation of the M.V. Arctic add greatly to the existing knowledge and have provided a factual basis for the development of a rational equation to represent the level ice performance not only of the M.V. Arctic itself but also of other ships which are not too dissimilar in shape and bow form.

13.3 The analysis and plotting of the data from the dedicated trials in continuous sheet ice indicates that the ice resistance to the M.V. Arctic is dependent on ship speed, V, and ice thickness, h, in the following manner.

(1) The velocity dependent component of ice resistance varies approximately linearly with velocity.

(2) The velocity dependent resistance also varies approximately with $h^{1.5}$.

(3) The breaking and submergence resistance not dependent on velocity varies approximately with h to the power of 1.8. In equations of the Kashtelyan type which have two non-velocity dependent terms, one varying with h and the other with h^2, this means that the h^2 term predominates.

The equations tested, in either their original or modified form, were those of Kashtelyan, Enkvist, Poznyak and Ionov and Carter. Of these, a variation of the Poznyak and Ionov equation modified in all three terms is tentatively selected as best representing the performance of the

M.V. Arctic. The selected equation of total resistance (ice and water) reduces to the following when the values of hull dimensions and bow geometry are inserted for the M.V. Arctic.

$$R_t = 3.33\ \sigma_f\ h^2 + 169\ h + 241\ Vh^{3/2} + R_{OW} \text{ (kilo Newtons)} \quad \ldots\ldots\ldots (5)$$

where σ_f = ice flexural strength (kilo Pascals)
h = ice thickness (metres)
V = ship speed (metres per second)

13.4 The full-power (11,000 kW) performance of the M.V. Arctic, with an Inerta 160 coating and an assumed dynamic hull/ice friction coefficient of 0.03, as given by the above modified Poznyak and Ionov equation, is shown in Figure 13.1 for an ice strength of 350 kPa. This indicates a maximum continuous mode capability of 1.0 metres of level ice at a speed of 0.8 m/s (1.6 knots).

13.5 The model test report states that "the ship will be capable of 1.5 knots through 2 ft of 100 psi ice". This is not inconsistent with the full-scale test results if account is taken of the model assumptions of a 690 kPa ice strength, a hull/ice friction of 0.15 and a power of 12,000 HP (900 kW). A non-dimensional plot of the modified Poznyak and Ionov equation correlates well with the model test results if a new interpretation is given to the model friction tests as discussed in Section 8.

13.6 Theoretical considerations suggest that the bow shape of the M.V. Arctic could be improved, particularly in the area of the shoulders. Ideally the tangent of the flare angle should exceed the coefficient of friction between hull and ice over the whole area of the bow in contact with ice if the ice is to be broken by bending rather than crushing.

13.7 The bubbler system on the M.V. Arctic appears to be ineffective from the available test data. The reason for this is not known but may be due to the vertical sides of the vessel and the already low friction provided by the coating of Inerta 160. There is no evidence that any of

the "bubbler on" tests were carried out in conditions of internal ice pressure and it is possible that the bubbler system would be effective under such conditions.

13.8 Performance of the M.V. Arctic in broken ice appears to conform reasonably with the predictions of Kashtelyan. However, a complete description of the broken ice environment was never recorded and a reliable indication of performance in broken ice cannot be predicted.

13.9 The M.V. Arctic test results indicate that the power provisions of CASPPR are adequate if the requirement of an Arctic Class 2 vessel is narrowly defined as its ability to transit 2 ft thick ice in the continuous mode. However, the voyage data shows that the minimum CASPPR power requirements are too low for unassisted operation of a Class 2 vessel in the ice conditions that may be met in zone 13 during the season now permitted.

13.10 As far as ice transiting performance is concerned, the instrumentation system installed in the M.V. Arctic was sufficiently comprehensive but not all sensors were functioning in the first two seasons. The data collected during voyages would have been more useful if more detailed logs of events, ice conditions and back-up readings had been kept. Some suggestions for improvement are given in Section 12.

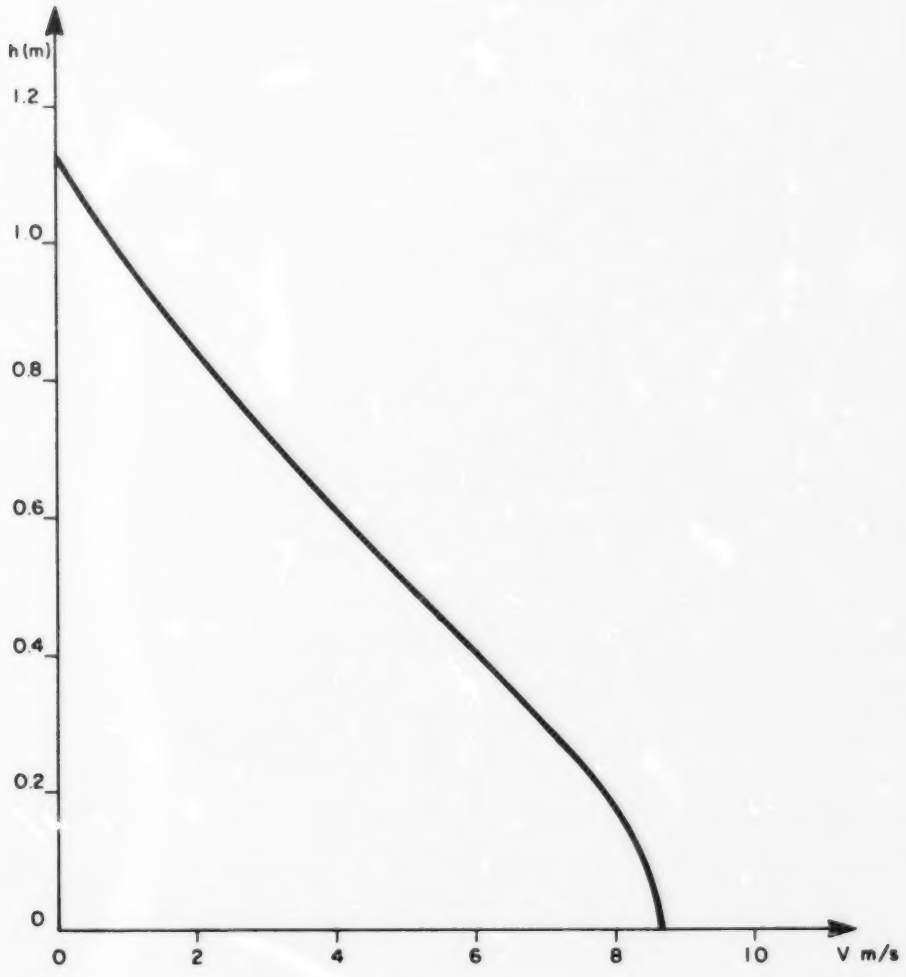

FIGURE 13.1 M.V. ARCTIC - SHEET ICE PERFORMANCE SHIP SPEED VS. ICE THICKNESS WITH FULL POWER.

σ_f = 350 kPa. f_d = 0.03